

SEARCH FOR SIGNAL ON PERCOLATION CLUSTER FORMATION IN NUCLEUS-NUCLEUS COLLISIONS AT RELATIVISTIC ENERGIES

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Abstract

The appearance of the strongly interacting matter mixed phase (MP) has been suggested to consider to understand qualitatively the regime change existence in the behavior of some centrality depending characteristics of events. The MP has been predicted by QCD for the temperatures around the critical temperature T_c and could be formed as a result of nucleon percolation in the density nuclear matter. Our main goal is to get a new experimental confirmation of the percolation cluster formation as an accompanying effect of the MP formation. To reach the goal, the experimental data on $Kr + Em$ - reaction at 0.95 GeV/nuc and $Au + Em$ - reaction at 10.6 GeV/nuc. with a number of target fragments $N_h > 8$, have been analyzed. The behavior of the distributions of the target and the projectile fragments have been studied. The experimental data have been compared of the data coming from the cascade-evaporation model. We can conclude that:

- the centrality of the collision could be defined as a number of the target g-fragments in $Kr + Em$ reactions at energies 0.95 A GeV/nuc and as a number of projectile F-fragments with $Z \geq 1$ in $Au + Em$ reactions at energies 10.6 A GeV/nuc;
- the formation of the percolation cluster sufficiently influences the characteristics of nuclear fragments;
- there are points of the regime changes in the behavior of some characteristics of s -particles as a function of centrality which could be qualitatively understood as a result of the big percolation cluster formation.

1 Introduction

Mixed Phase: Studying the behavior of the hadron-nuclear and nuclear-nuclear interactions characteristics as a function of collision centrality Q is an important experimental method to get information about changes of the nuclear matter phase, because the increasing Q could lead to the growth of the nuclear matter baryon density. In other words, the regime change in the behavior of some centrality depending characteristics of events is expected by varying of Q to be a signal on phase transition. This method is considered to be the best tool for reaching the quark-gluon plasma phase of strongly interacting matter. Some experimental results have already demonstrated the existence of the regime changes in the event characteristics behavior as a function of the collision centrality [1]-[8]. The

regularity is observed for hadron-nuclear [1]-[2], heavy [3]-[7] and light nuclear [8] interactions in a large domain of nuclear masses and initial energies. It has been also observed for the behavior of some centrality characteristics of π -mesons, nucleons, fragments, strange particles, and even for those of J/ψ . So, the regime changes under consideration can not be related with the existence of the predicted QCD point for the hadronic matter quark-gluon phase transition and therefore it has been suggested [9] to consider the appearance of the strongly interacting matter mixed phase (MP) for qualitative understanding of the regularity. MP has been predicted by QCD for the temperatures around the critical temperature T_c and could be formed as a result of nucleon percolation in the density nuclear matter. It is related with the following.

Percolation cluster: It is well known that the statistical and percolation theories can describe critical phenomena best of all and from the other hand the regime changes under consideration have been also observed for small density and temperature at which the conditions to apply statistical theories are practically absent. So, one could say that the percolation approach is practically the only one to describe the results. Paper [10] discusses that percolation clusters are much larger than hadrons, within which color is not confined; deconfinement is thus related to the percolation cluster formation. This is the central topic of the percolation theory, and hence, the connection between percolation and deconfinement seems to be very likely [11]. So, the experimental information on the particular conditions of the MP formation could be very important to fix the onset stage of deconfinement for its future identification. To extract the signals on the accompanied effects of MP could be one of the ways to get the experimental information on the MP formation. The percolation cluster formation could be one of these effects where the MP formation starts at high energies.

Physical picture: We can consider the following physical picture to understand qualitatively the mentioned above.

At low energies: At some critical values of centrality Qc the compressed compound nuclear system could appear. In this system the thermal equilibrium could be established as a result of Fermi motion and the percolation occurs that would result in big percolation cluster formation which will then be fragment on the nuclear fragments. So the process of the percolation cluster could influence the nuclear fragments characteristics. This idea was experimentally tested in [12] for high energy interactions. Section 2 shows the experimental results for the heavy nuclear interaction at the low energies.

At middle and high energies. First we have to note that in comparison with the low energy interaction at middle and high energies the contributions of multiparticle collisions have to increase strongly (particularly in the region of central collisions near Qc) and the quark-gluon degree of freedom of the matter could appear. Paper [13] discusses that the hadron-chemical-equilibrium could be established as a result of multiparticle collisions during the heavy nuclear interactions. In this system the percolation could occur and the big percolation cluster might be formed. But in comparison with the low energy picture in this case the percolation cluster could consist of hadrons and quarks representing a mixed phase. One more issue to be considered in section 2 is a possibility to get the signal on percolation cluster formation in heavy nuclear interactions at high energies.

As we have mentioned above, the idea that the process of the percolation cluster could influence the nuclear fragments characteristics was experimentally tested in [12]. It will be the main idea to get the information on the percolation cluster formation. To reach

this goal, two ways of Q determination were used in paper [12]. In one way the values of Q were determined as a number of protons emitted in one event and in the second one – as a number of protons and fragments emitted in one event. The events of ^{12}CC -interaction at the momentum of 4.2 A GeV/c were used [14]. The experimental data were compared with the simulation data coming from the quark-gluon string model (QGSM) without the nuclear fragments [15]. It is supposed that the behavior of the events' number dependent of Q determined the both ways should be similar if there are no clusters as a source of fragments and they would differ if the cluster exists as one. It was obtained that the form of the distribution strongly differs for the distribution with different Q determination ways. In the second case the two steps structure was indicated in the behaviour of the distribution which could not be described by the model. This result has demonstrated that the influence of nuclear fragmentation processes on the behaviour of the events number dependent of Q has a critical character. But it is clear that the light nuclear interaction is not a good object to study the fragmentation processes. The main properties of the nuclear fragmentation were obtained at low and middle energy collisions of heavy nuclei [16]. So, we turn to the low and high energy collisions of heavy nuclei and our main goal is to get a new experimental confirmation of the percolation cluster formation as an accompanying effect of the MP formation.

Centrality of the collisions: Before discussing the experimental results we would like to touch upon one more question which is very important for the centrality experiments. It is clear that the centrality of collisions Q can not be defined directly in the experiment. In different experiments the values of Q are defined as a number of identified protons, projectiles' and targets' fragments, slow particles, all particles, as the energy flow of the particles with emission angles $\theta \simeq 0^\circ$ or with $\theta \simeq 90^\circ$. Apparently, it is not simple to compare quantitatively the results on Q -dependencies obtained in different papers and from the other hand the definition of Q could significantly influence the final results. So we believe it is necessary to understand what centrality Q is. Usually for a chosen variable to fix Q it is supposed that its values have to increase linearly with a number of colliding nucleons or baryon density of the nuclear matter. The simplest mechanism that could give this dependence is the cascade approach. So, we have used one of the versions of the cascade-evaporation model CEM [17] to choose the variable to fix Q for studying the centrality dependence of the event characteristics.

2 Experiment

Distribution of the fragments. To reach the goal, we have analyzed the experimental data on $\text{Kr} + \text{Em}$ - reaction at 0.95 GeV/nucleon [18] and $\text{Au} + \text{Em}$ - reaction at 10.6 GeV/nucleon [19]. We have considered the events with a number of $N_h > 8$ to select the heavy nuclear collisions (in papers [18]- [19] this condition was not used). According to the idea mentioned above on the centrality event selection, we have studied the behavior of the distributions of the target fragments (g - and h - fragments) and the projectile fragments with charge $Z \geq 1$ (F -fragments). The experimental data have been compared of the once coming from the CEM [17].

The $\text{Kr} + \text{Em}$ reactions at 0.95 GeV/nucleon. Fig 1a-f shows the yields of g -, h - and F -fragments in the $\text{Kr} + \text{Em}$ (at 0.95 GeV/nucleon, Fig. 1 a-c.) and in $\text{Au} + \text{Em}$ (at 10.6 GeV/nucleon, Fig. 1d-f.) reactions. The results coming from the CEM are also drawn. We

can see that :

The g -fragments experimental multiplicity distribution (N_g) for the $Kr+Em$ reactions is well described by the model (Fig. 1a). We would remind that in the framework of the CEM g -fragments are considered as the results of cascading collisions in the target spectator and participant. So N_g could be used to fix the centrality of collisions (result I).

The target h -fragments multiplicity (N_h) distribution shape for the $Kr+Em$ reactions (Fig. 1b) cannot be described by the CEM in the region of N_h values $15 < N_h < 32$. If we remember that the N_h is the number of the final state target fragments in the event which is the sum of the target black fragments (N_b) and N_g , we would say that the CEM can't describe the multiplicity distributions of b -particles which are the slowest target fragments and thus they have to get much more information on the state of the nuclear target. In a recent paper [20] one of the authors using CEM has shown that to describe fully the b -particles yields, it is necessary to take into account the percolation mechanism and formation of big percolation cluster. So, we could assert that this observed difference between the behavior of the experimental and model N_h - distributions, is related with the formation of the big percolation cluster (result II);

The behavior of the experimental distribution of projectile fragments with $Z \geq 1$ produced in $Kr + Em$ collisions (Fig. 1c) is not in agreement with the result coming from the CEM in a full area of the N_F definition either. At the point $N_F = 2$ the model gives the result more than one order higher in comparison with the experiment. Two other N_F regions are observed (at $7 < N_F < 14$ and $30 < N_F < 40$) where the obtained model and the experimental data do not agree with each other and we can see that the difference has a critical character because it appears only at some values of N_F (result III). The formation of the big percolation cluster could give this critical behavior, for example, as the result of appearance of the physical picture described above (for low energy interactions).

The Au+Em reactions at 10.6 GeV/nuc. The experimental distribution of g -particles from $Au - Em$ reactions (Fig. 1d) can not be described by the model in full region of the N_g definition. We can separate some region in the relative between the behaviors of the experimental and model distributions. In the region of $N_g < 5$ the model can describe the experimental distribution. In the region of $N_g > 15$ the experimental values of N_i decrease with N_g while the values coming from the model are constant in the region $15 < N_g < 40$. The model could not describe the distribution of h -particles in a full region of the N_h -definition either, that is seen from Fig. 1e. The model could only describe the experimental distribution of N_h in the region of $22 < N_h < 32$. So, we can say that for the reaction under consideration the N_g as well as the N_h could not be used to fix the centrality of collisions (result IV). We believe that the result could also be understood qualitatively in the framework of the above-mentioned physical picture (for high energy interactions). In a recent paper [21] the bond percolation model is used to interpret 10.2 GeV/c $p + Au$ multifragmentation data. The critical value of the percolation parameter $p_c = 0.65$ was found from the analysis of the intermediate mass fragments charge distribution.

The distribution of projectile fragments with $Z \geq 1$ produced in $Au + Em$ collisions is in good agreement with the result coming from the CEM. So, we can see that the projectile fragments are produced by the mechanism similar to the cascade-evaporation one and N_F could be used to fix the centrality for these reactions (result V).

Correlation. It is clear that the obtained results are not sufficient to confirm fully the percolation cluster formation especially at high energy collisions for which the contributions of multiparticle collisions have to increase strongly, and particularly in the region of central collisions near the critical values of centrality. As it has been mentioned, at these high energies the hadron-chemical-equilibrium was established and the percolation could occur. But in comparison with the low energy physical picture, in this case the percolation cluster could consist of hadrons and quarks and represents the mixed phase.

Thus, one needs to get additional information in future to confirm the percolation cluster formation.

A number of the final-state-relativistic single charged particles (s) in the emulsion experiments (it is called the multiplicity of the shower particles and is denoted by $\langle n_s \rangle$) might be most sensitive to the dynamics of the interaction at high energies (as well as the values of pseudorapidity η of s -particles). So, we have studied the correlation between the characteristics of s -particles and the values of centrality. As we have mentioned above, to fix the centrality, one might use the variable N_g for $Kr + Em$ reactions and N_F for $Au + Em$ ones. Here we discuss the results of our study.

Fig. 2a-c presents the average values of multiplicity $\langle n_s \rangle$ for s -particles produced in $Kr + Em$ and $Au + Em$ reactions and the average values of pseudorapidity for s -particles produced in $Au + Em$ reactions. We can say that there are two regions in the behavior of the values of $\langle N_s \rangle$ as a function of N_g for the $Kr + Em$ reaction (Fig. 2a). In the region of: $N_g < 40$ the values of $\langle N_s \rangle$ increase linearly with N_g , here the CEM also gives the linear dependence but with the slope less than the experimental one; $N_g > 40$ the CEM gives the values for N_s greater than the experimental observed ones, the last saturates in this region, the effect could not be described by the CEM. It has been previously observed in emulsion experiments [16]. It is clear that there should be some effects which could stop (or sufficiently moderate) the increase of N_s . The effect of the percolation cluster formation could be one of those effects. The moderation of the values of N_s as a function of N_F is also observed for the $Au + Em$ reaction at 10.6 GeV/nucleon (Fig. 2c) near the point of the $N_F \simeq 40 - 50$ these should be a point of the regime change which is absent for the distribution coming from the CEM.

Thus, we can say that the effects which could stop (or sufficiently moderate) the dependence of $\langle N_s \rangle$ as a function of centrality appear at some values of N_g and N_F . It strengthens the result VII because the process of percolation cluster formation is a critical effect which appears at some critical values of centrality. If we compare the behavior of the experimental and theoretical distributions for the values of η of s -particles produced in the $Au + Em$ reaction as a function of N_F (Fig. 1c), we would get one more confirmation on the existence of the point $N_F \simeq 40 - 50$, behind which the values of η are systematically less than the CEM expectation. But in the region of $N_F > 40 - 50$ the model describes the experimental distribution rather well.

So, we can say that the points of the regime change are observed in the behavior of the characteristics of s -particles as a function of centrality. In the central collisions region the increase of the average values of multiplicities are sufficiently moderate (or stopped) and the average values of η decrease and could not be described by the CEM. It could be qualitatively understood within the formation of the big percolation cluster.

3 Conclusion

We can conclude that:

- the centrality of collision could be defined of as a number of the target g-fragments in $Kr+Em$ reactions at energies 0.95 A GeV/nuc and as a number of projectile F -fragments with $Z \geq 1$ in $Au + Em$ reactions at energies 10.6 A GeV/nuc;
- the formation of the percolation cluster sufficiently influences the characteristics of nuclear fragments;
- there are points of the regime changes in the behavior of some characteristics of s -particles as a function of centrality which could be qualitatively understood as a result of the big percolation cluster formation.

References

- [1] I. Chemakin et al. The BNL E910 Collaboration, E-print:nucl-ex/9902009, (1999).
- [2] Ron Soltz for the E910 Collaboration. J. Phys. G: Nucl. Part. Phys. **27**, (2001) 319-326
- [3] Fu-Hu Liu et al. Phys. Rev. **C 67**, 047603 (2003)
- [4] A. Abduzhamilov et al., Z. Phys. C 40, 223 (1988)
- [5] F.H. Liu, Chin. J. Phys. (Taipei) **40**, 159 (2002)
- [6] A.L.S. Angelis et al. The HELIOS/3 Collaboration, Eur. Phys. J. **C13**, 433-452 (2000).
- [7] M.C. Abreu et al. Phys.Let. **B450**,456 (1999); M.C. Abreu et al. Phys.Let. B410, 337,(1997); M.C. Abreu et al. Phys.Let. **B410**,327, (1997); M.C. Abreu et al. By NA50 Collaboration : Phys.Lett.**B499**,85-96, (2001).
- [8] M.K. Suleimanov et al., Phys.Rev. **C 58**, 351, (1998).
- [9] A.N. Sissakian et al. Selected Transactions of the University "DUBNA". Collected Articles., 44-68 (2004)
- [10] H Satz. Rept.Prog.Phys. **63**,1511,(2000)
- [11] H. Satz, Nucl. Phys. **A 642** , 130, (1998); G. Baym, Physica **96A** , 131 (1979); T. Celik, F. Karsch and H. Satz, Phys. Lett. **97 B**,128, (1980).
- [12] M.K. Suleymanov et al. Nucl.Phys.**A 734S**, E104-E107, (2004); M.K. Suleymanov et al. Proceedings of the Conference: Bologna2000, Bologna, Italy, 375,(2000).
- [13] P. Braun-Munzinger , J. Stachel, Christof Wetterich. Phys.Lett. **B596**,61-69 (2004).
- [14] N. Akhababian et al.- JINR Preprint 1-12114, Dubna (1979); N.S. Angelov et al.- JINR Preprint 1- 12424, Dubna (1989) ; A.I. Bondorenko et al., JINR Communication, P1-98-292, Dubna (1998).

- [15] N.S. Amelin, L.V. Bravina, Sov. J. Nucl. Phys. **51**, 211 (1990) ; N.S. Amelin et al., Sov. J. Nucl. Phys.**50**, 272 (1990).
- [16] W. Resisdorf, E-print: nucl-ex/0004008 (2000).
- [17] G.J. Musulmanbekov, Proc. of the 11th EMU01 Collaboration Meeting, Dubna, Russia, (1992); Proc. 11th Int. Symp. on High Energy Spin Phys., Bloomington, (1994);AIP Conf. Proc. **343**, 428 (1995).
- [18] S.A. Krasnov et al., Czech. J. Phys. **46**, **No.6** , 531 (1996).
- [19] M.I. Adamovich et al., Phys. Lett. **B 352** (1995).
- [20] G. Musulmanbekov, A. Al-Haidary. Russian Journal of Nucl. Phys., **66**, 1-9 (2003).
- [21] M. Kleine Berkenbusch et al., Phys. Rev. Lett.**88**, 022701 (2002)

Fig. 1a-f. Distribution of the target a) g - fragments; b) h -fragments; projectiles' c) F -fragments produced in the $Kr + Em$ reactions at 0.95 GeV/nucleon and target d) g - fragments; e) h -fragments; projectile f) F -fragments produced in the $Au + Em$ reactions at 10.6 GeV/nucleon. It also gives the results coming from the CEM calculation.

Fig. 2a-c. a) average values of s - particles multiplicity produced in the $Kr + Em$ reactions at 0.95 GeV/nucleon as a function of N_g ; average values of the b) multiplicity; c) pseudorapidity of s -particles produced in $Au + Em$ reactions at 10.6 GeV/nucleon as a function of N_F . It also shows the result coming from the CEM.

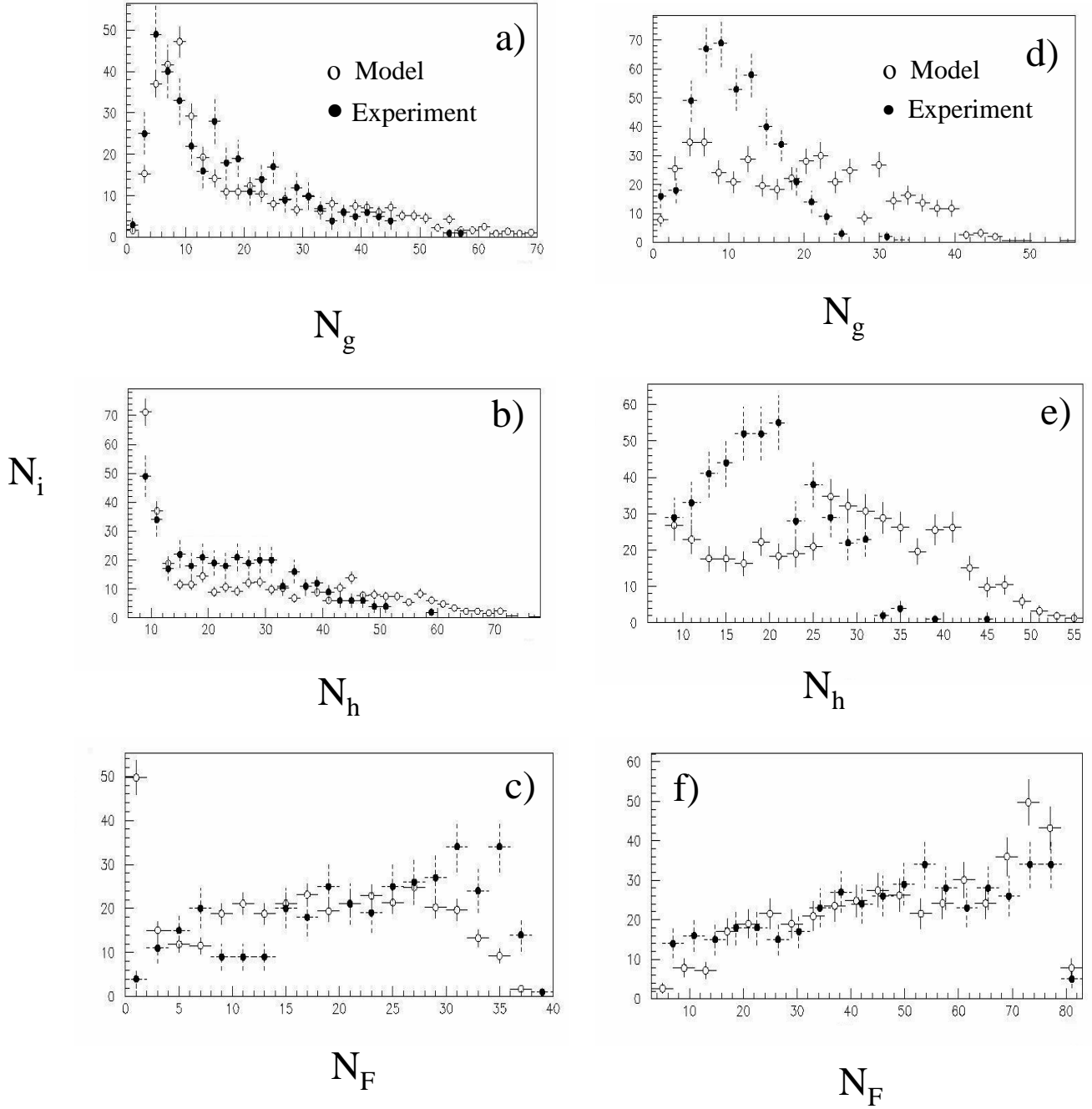


Fig 1a-f. Distribution of the target a) g - fragments; b) h-fragments; projectiles' c) F-fragments produced in the Kr + Em reactions at 0.95 GeV/nucleon and target d) g - fragments; e) h-fragments; projectile f) F-fragments produced in the Au + Em reactions at 10.6 GeV/nucleon. It also gives the results coming from the CEM calculation.

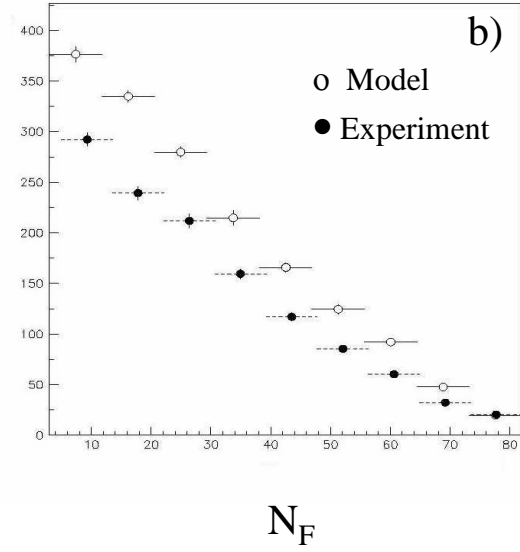
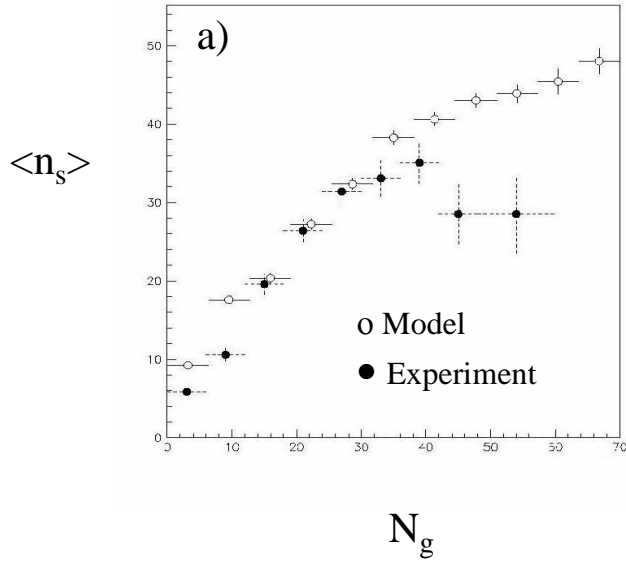


Fig. 2a-c.
a) average values of s - particles multiplicity produced in the Kr + Em reactions at 0.95 GeV/nucleon as a function of N_g ; average values of the
b) multiplicity; c) pseudorapidity of s-particles produced in Au + Em reactions at 10.6 GeV/nucleon as a function of N_F . It also shows the result coming from the CEM.

